SOFIA Vacuum Pump System Concept of Operations

APP-DA-PLA-PM17-2074

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1. INTRODUCTION

1.1. Purpose

The purpose of this document is to describe the concept of operations for a facility vacuum pump system (VPS) for the Stratospheric Observatory for Infrared Astronomy (SOFIA). It outlines expected operational scenarios that will drive the requirements for the system and indicates the relevant responsibilities of the various stakeholders.

1.2. Scope

The VPS is needed for evacuating enclosed science instrument (SI) and telescope assembly (TA) Instrument Flange (INF) "Tub" [1] volumes when needed and support on-aircraft vacuum requirements of the science instruments. The VPS will comprise vacuum pumps permanently affixed to the aircraft and associated instrumentation such as pressure valves, pressure monitors, hoses and flanges. The VPS will be implemented and maintained by the Platform Project, as part of the observatory's infrastructure. Science Project Mission Operations will provide the vacuum lines from the VPS connections located next to the Telescope Assembly (TA) Counterweight Plate (CWP) to the SI and any hardware internal to the INF Tub as may be necessary for evacuation of a pressure coupler, while the Platform Project will include the vacuum lines between the CWP and the INF Tub as part of the VPS.

A context diagram depicting the scope of the VPS and the relevant interfaces to other subsystems (and identifying the applicable ICDs) is provided as Figure 1.2-1.

1.3. Referenced Documents

SOF-DF-SPE-SE01-004	SOFIA Airborne System Requirements
SOF-DA-ICD-SE03-036	Cable Load Alleviator Device / Science Instrument Cable Interface (TA_SI_01)
SOF-DF-ICD-SE03-037	Telescope Assembly/Science Instrument Mounting Interface ICD (TA_SI_02)
SOF-DF-ICD-SE03-018	Telescope Assembly/Aircraft System Exhaust Tube and Vacuum Lines Interface (TA_AS_11)
SOF-DF-ICD-SE03-048	Telescope Assembly / Mission Controls and Communications System (MCCS) Physical Interface (TA_MCCS_P)
SOF-DA-ICD-SE03-2022	Vacuum Pump System to Science Instrument ICD (VPS_SI_01)
SOF-AR-ICD-SE03-2029	Principal Investigator Patch Panel to Principal Investigator Equipment Rack(s) Interface (MCCS_SI_05)
APP-DF-ICD-SE03-2038	Global Power Budget Interface Control Document

[1] The interior portion of the INF forward of the Pressure Window Subassembly and aft of the instrument mounting flange (IMF) is commonly referred to as the INF "Tub".

APP-DF-LIS-SE03-2042 Platform Parameter List
APP-DF-PLA-PM23-2000 SOFIA Airborne Platform Logistics Plan
SCI-US-PLA-PM17-2065 SOFIA Facility Science Instrument Maintenance Plan
Helium-3 and Helium-4, Keller, William. New York: Plenum Press 1969
"Cryogenics, Chapter 7" R. J. Donnelly. A Physicist's Desk Reference: Second Edition of the *Physics Vade MecumEd*. New York, American Institute of Physics (1989).
"Logarithmic Singularities of Specific Heat and Related Properties of Liquid ^{4}He Near λ Point", Simanta, C. and Jain, Y. arXiv:cond-mat/0612279 (2006)

1.4. Background

Uses of the VPS may include pumping of internal SI optical paths, pressure couplers, and/or the SI/TA interface volume (the nature of which depends on the specifics of a given SI/TA connection, i.e., SI to instrument mounting flange, SI via pressure coupler to gate valve, or window to gate valve – see ICD TA_SI_02) to protect hygroscopic SI entrance windows against environmental damage.

Select SI systems use detectors that are required to operate at temperatures lower than the liquid helium bath temperature of 4.2 K for optimal performance. These SIs will use the VPS to pump on the liquid helium bath to lower the temperature to between 1.5 and 2 K

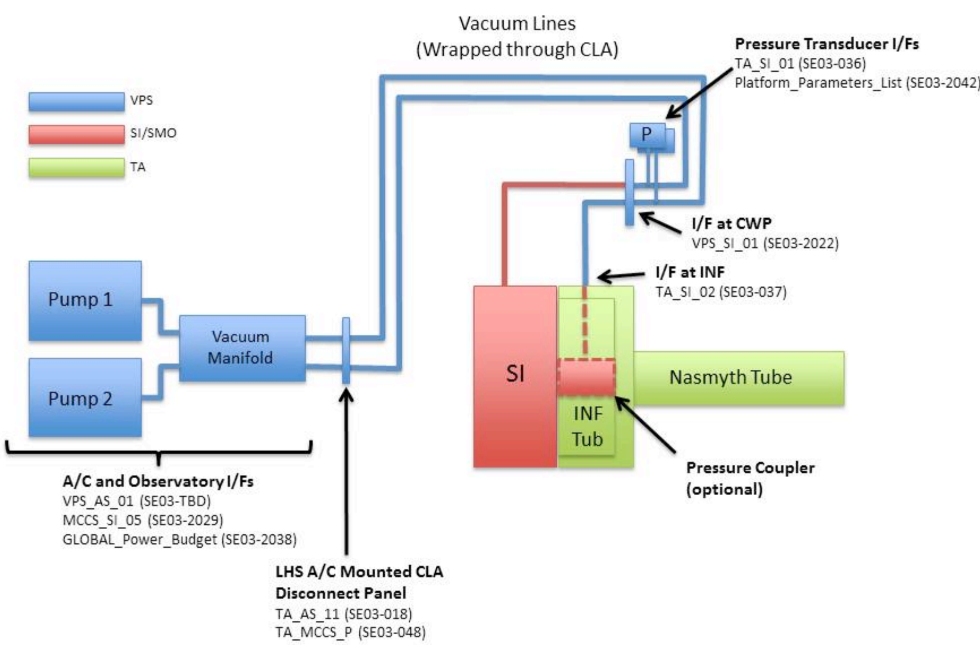

Figure 1.2-1: Contextual diagram for the SOFIA Vacuum Pump System. Blue items indicate elements of the VPS, including vacuum lines wrapped through the CLA , while red indicates SI elements, not within the scope of the VPS. Relevant interfaces for the VPS vacuum lines are indicated.

2. CONCEPT FOR THE SOFIA VACUUM PUMP SYSTEM

2.1. System Overview

As stated in paragraph 3.1.26 of the SOFIA Airborne System Requirements document (SOF-DF-SPE-SE01-004), SOFIA is required to have a vacuum pump system for pumping on cryogenic reservoirs and evacuating various volumes associated with the SI/TA interface. Vacuum pumps will be part of the facility and will not be removed during an exchange of SIs. As such, they will be located in the cabin and will draw electrical power from the aircraft during flight and do not place a burden on the SI power budget.

The VPS may be used in continuous operation during SI operations, depending on the specific needs of an individual SI. For Tub evacuation, a single pump-down to pressures less than about 100 Pascal followed by either sealing the Tub or back-filling with dry nitrogen would be the normal operation. The specifics of the relevant operational scenarios are described in Section 2.4.

The pressure will need to be monitored at multiple locations and the pumping speed regulated. Vacuum lines are passed through the cable load alleviator (CLA). Although this may reduce the overall pumping speed due to the reduced conductance of the long lines, especially at low pressures, this is necessary to locate the VPS off of the TA.

2.2. Operational Environment

The VPS spans multiple sections of the SOFIA system, with vacuum pumps and regulators in the cabin, vacuum lines wrapped through the CLA and connections being made to the INF and SIs. Each component may thus be exposed to differing environments.

The vacuum pumps and the associated pressure regulation manifold, consisting of pressure gauges, transducers, and valves operate as an aircraft subsystem. They will be mechanically mounted to the aircraft, and supplied electrical power via the Power Distribution Subsystem (PDS, see APP-DF-ICD-SE03-2038 and SOF-AR-ICD-SE03-2029 para. 3.2.1.3), which includes two (2) Circuit Breakers at the Observatory Power Panel (OPP) to protect the platform PDS power feed wires and to control the application of power to the VPS power interfaces. These circuit breakers would not be used for routine on/off control of the VPS.

Pressure measurements will be made at multiple locations with transducer data obtained added to aircraft housekeeping in accordance with APP-DF-LIS-SE03-2042, Platform Parameter List. This will require the routing of power and signals through the CLA to and from pressure transducers, via patch panel and cable interfaces defined in SOF-DA-ICD-SE03-036 and SOF-DF-ICD-SE03-048. Valves for regulation of the pumping rate will need to be accessed during operations by SI personnel for regulation in response to pressure needs internal to the SI as described in the use cases in Section 2.4. Because this may be occurring during astronomical observations, access to these VPS controls must be accessible to PI team personnel and other mission crew without the need to cross boundaries or cage the telescope. Any personnel accessing the VPS, either for operation or maintenance, should be trained in vacuum pump operation.

The vacuum pumps will vent to the cabin and operate under the environmental conditions (pressure, temperature, etc.) normally found in the cabin. As these conditions may change with altitude and impact the performance of the VPS, adjustability in the pumping speed is necessary. The VPS will be required to meet airworthiness and environmental (vibration, max loads, etc.) requirements.

The vacuum lines will need to be wrapped through the CLA. The practicable pumping speed at the instrument will be affected by the cross-section and length of the pumping lines and, therefore, the determination of the physical location of the pumps will require a design trade considering these factors as well as access considerations. However, a minimum length of 10 meters is indicated within SOF-DA-ICD-SE03-036 (TA_SI_01), with additional lengths needed for connects between the VPS pumps and manifolds to the CLA Disconnect Panel, and between the CWP and the INF and/or SI cryostat(s).

When telescope and/or science instrument volumes are connected to the VPS, they become sensitive to the possibility of backflow should the pumping be interrupted. To ensure the safety of the systems being pumped on, and to preclude the need for overboard venting of pump exhaust flow and oil mist separators, only oil-free pumps should be used. Furthermore, automatic shut-off valves are necessary in the case of power loss.

The VPS may need to perform multiple operations on a single flight (cryogen bath pumping and tub evacuation, pumping on two cryogen baths, etc.), possibly simultaneously; therefore, multiple independently controllable pumps will be necessary. This also provides redundancy that improves overall reliability of the system. There is no requirement for a single vacuum pump to perform multiple operations simultaneously. Although there is currently no envisioned use case for which it is critical to have two pumps operating simultaneously, continuous operation for the duration of a flight of at least one pump will be a normally occurring scenario.

2.3. Support Environment

The logistical support and maintenance of the VPS and its component parts will be covered by the SOFIA Airborne Platform Logistics Plan (APP-DF-PLA-PM23-2000). This includes maintenance of pumps as well as spare pumps, vacuum lines, flanges, o-rings, clamps, etc. On aircraft spare parts will be limited to those necessary for inflight troubleshooting. This will involve only operational changes and/or possible reconfiguration of the vacuum lines at the vacuum pump interfaces not requiring the use of tools. Maintenance, repair, and/or replacement of other components will be limited to ground support activities only.

Vacuum lines and other supporting equipment from the interface to the SI need to be provided by the SI team and become part of standard SI maintenance (see the SOFIA Facility Science Instrument Maintenance Plan, SCI-US-PLA-PM17-2065, for details).

Procedures will need to be written for pump-down and regulation of cryogen baths, pumping of the INF Tub, and other uses of the VPS. Regular inspections will be necessary to ensure the health of the vacuum system. This includes, but is not limited to, inspection of flanges, o-rings, valves and vacuum lines for leaks, breaks and debris.

2.4. Use Cases

2.4.1. INF Tub evacuation

The instrument flange (INF) is a subassembly at the end of the Nasmyth tube and provides the interface of the science instruments to the telescope assembly (for detailed information see SOF-DA-ICD-SE03-037 (TA_SI_02), Telescope Assembly/Science Instrument Mounting Interface Control Document). The interior portion of the INF forward of the Pressure Window Subassembly and aft of the instrument mounting flange (IMF) is commonly referred to as the INF "Tub". This volume may contain a pressure coupler, a window assembly, or remain empty depending on the particular SI's interface design. The inside walls of the INF are lined with an insulation layer and the volume of the Tub, interior to the insulation, is 196 liters. The cabin side of the INF has two KF-25 connections for vacuum lines. On the interior side are threads to allow for a vacuum line pass-through to a pressure coupler, should only the pressure coupler be pumped on.

Because the window materials for the SIs may be hygroscopic, pumping on the INF Tub (with a optional, subsequent backfill of dry nitrogen) or pressure coupler protects the windows against condensation that may occur when the instruments are cooled down or when the aircraft descends. The volume of the Tub is relatively small and the pump down to adequate low pressures, less than about 100 Pascals (800 mTorr), can be accomplished in about 10 minutes or so.

Pumping of the Tub or pressure coupler may occur as part of the installation procedure of an SI, depending on its needs. Additionally, pumping may occur after closing the gate valve in preparation of descent. A backfill with dry nitrogen is not a requirement of flight operations and if desired, would be accommodated with GSE post-flight.

2.4.2. Cryogen Bath Pumping

Because infrared instruments are sensitive to wavelengths emitted by warm objects, the operation of the instruments at cryogenic temperatures is necessary. This is accomplished through the use of gases that have been cooled into liquids and poured into cryostats. When the cryogen bath is allowed to vent to atmospheric pressure, the SI components in contact with the bath will maintain the boiling temperature of the cryogen until it is all boiled away. The boiling temperatures for liquid nitrogen (LN2) and liquid helium (LHeI) are 77 K and 4.2 K, respectively. Cooler temperatures can be reached by pumping on the cryostat, which reduces the pressure above the bath with a resultant reduction of the boiling temperature.

FIFI-LS uses this method and routinely operates its detectors at temperatures between 1.6 – 1.8 K. This is below the so-called "lambda point" (T = 2.1768 K), which marks the phase transition to liquid helium's superfluid state (LHeII). At these temperatures the vapor pressure of LHeII is on the order of 1000 Pascals. Accomplishing the reduction of temperature is a process that requires frequent manual control over the pumping flowrate, while monitoring the cryostat bath temperature to follow a desired temperature gradient, which minimizes consumption of the cryogen to optimize the hold time. Typically, this process would occur before takeoff and takes 1.5 – 2 hours, during which about 1/3 of the cryogen reservoir is converted from liquid to gas. The calculations in Appendix B show that over 3800 liters of gas for every liter of liquid need to be pumped to reach 1.6 K. FIFI-LS has three cryogen reservoirs, one for LN2, one for LHeI, and one for LHeII. Only the third is actively pumped on and it has a volume of 3.12 liters. To reach 1.6 K in 1.5 hours thus requires a minimum pumping speed of about 2.25 liters/second.

The amount of time needed to reach cooler temperatures and the coldest temperature practically achievable are functions of the pumping speed and the heat load on the bath (see Appendix B). FIFI-LS is expected to have a heat load of about 30 mW. At this heat load and a desired temperature of 1.8 K, a minimum pumping speed of about 0.5 liter/second are needed to maintain this temperature. As lower temperatures have correspondingly lower vapor pressures, this requirement goes up quickly. At 1.6 K the vapor pressure is half the value as at 1.8 K, and thus the required pumping speed to maintain this temperature for the same heat load is doubled.

Although these are relatively mild pumping speeds, it is prudent to develop a system with capabilities compatible with the needs of future instrumentation. An order of magnitude higher heat load dissipation (i.e., 300 mW and 5 liters/second pumping speed) is easily accommodated with little cost and risk given current commercially-available vacuum pump technology.

Cryogen bath pumping may occur simultaneously with pumping of the INF Tub depending on installation and flight schedules.

2.4.3. Other SI scenarios

The specific designs and vacuum requirements of future instrumentation is unknown at this point; however, one can imagine other uses being desired, including pumping on liquid nitrogen cryogen baths or the pumping out of optical paths. The VPS is not intended to be used to support high vacuum (i.e., P < 0.1 Pascals) and likely would not be able to achieve these pressures considering the line length through the CLA.

3. SUMMARY OF IMPACTS

The primary stakeholders of the VPS are the science instruments. However, the design details of the VPS will not have a significant impact on the SI design, i.e., there are minimal impacts on the mass budget of the SI. Procurement and maintenance of any necessary vacuum lines, gauges, and valves that would be used between the instrument and the VPS interface on the CWP are the responsibility of the SI. Procedures for pumping/cooldown will need to be developed specific to the needs of the individual SI.

Implementation and design of the VPS is the responsibility of the Platform Project. This includes the detailed design, FMEA, airworthiness reviews, environmental acceptance, and verification of requirements.

APPENDIX A. ACRONYMS

CLA	Cable Load Alleviator
CWP	Counterweight Plate
FMEA	Failure Modes and Effects Analysis
I/F(s)	Interface(s)
IMF	Instrument Mounting Flange
INF	Instrument Flange
K	Degrees Kelvin
LHe/LHeI	Liquid Helium
LHeII	Superfluid Helium
LN2	Liquid Nitrogen
OPP	Observatory Power Panel
PDS	Power Distribution Subsystem of Mission Controls and Communications System (MCCS)
SI	Science Instrument
SOFIA	Stratospheric Observatory for Infrared Astronomy
TA	Telescope Assembly
VPS	Vacuum Pump System

APPENDIX B. LIQUID HELIUM PUMPING CALCULATIONS

At atmospheric pressure, liquid helium boils at a temperature of 4.2 K. In the boiling process, energy is removed from the bath with no change in temperature, as the helium makes the phase change from liquid to gas. The latent heat of vaporization (L, in units of J mol^{-1}) is the energy released when the helium makes the phase transition from liquid to gas.

Through an evaporative cooling process, lower temperatures can be attained. This is accomplished by pumping on the dewar, which reduces the pressure above the liquid, resulting in a lower boiling temperature for the bath. As the temperature decreases, the vapor pressure of the liquid also falls, and cooling becomes less effective; therefore, for a given liquid there is a practical limit on this process, based on the pumping speed of the vacuum system and the energy inputs to the bath.

The energy needed to be removed from the system per mole of liquid helium, with specific heat C_s (units of J mol^{-1} K^{-1}), to reduce the temperature by $\Delta T = T_1 - T_2$ is given by

$$\Delta E = \Delta T * C_s(T)$$

in units of J mol^{-1}. The fraction of the liquid that needs to be boiled off is thus the ratio of this energy to the latent heat, i.e., $\Delta E/L$. To cool liquid helium below its boiling point requires a significant reduction in the volume of liquid in the bath.

One peculiar property of liquid helium is that at a temperature of 2.1768 K, there is another phase transition from a normal liquid to a superfluid state. This transition (called the lambda point) is marked by a sudden increase in the specific heat (see Figure B.1). Because of the rise of the specific heat near the lambda point (while the latent heat remains relatively constant) more liquid needs to be converted to gas to reduce the temperature below this point.

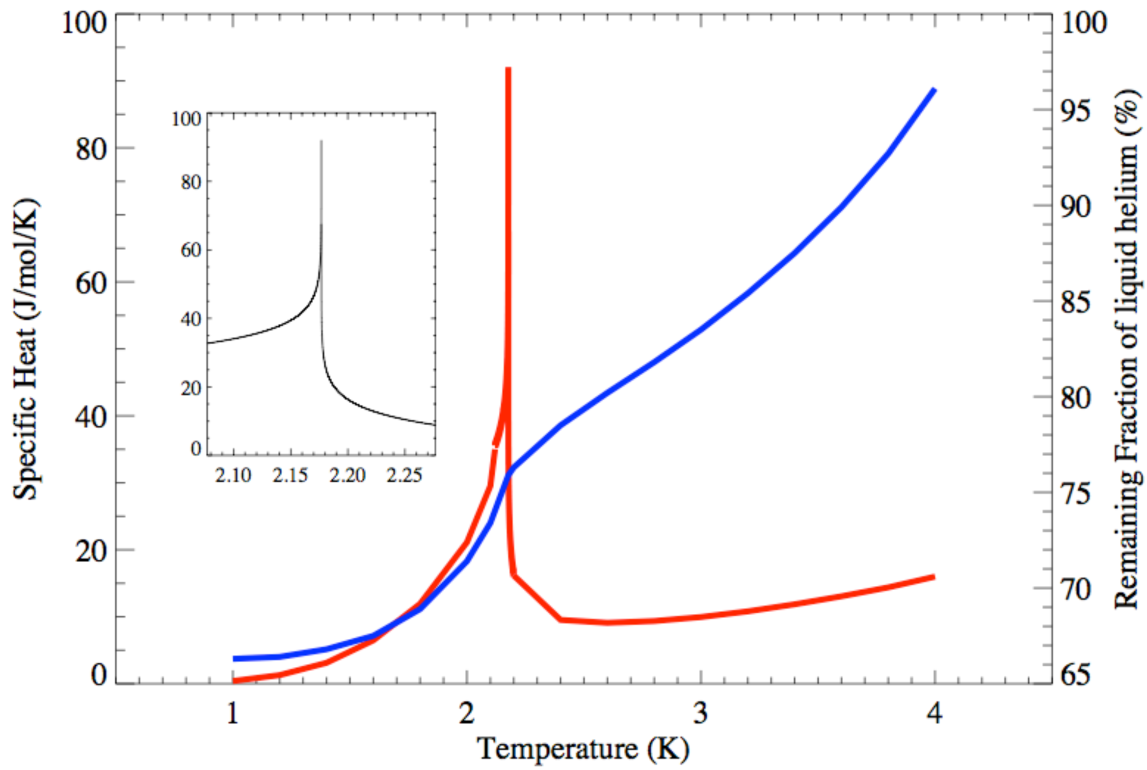

Figure B.1: Specific heat of liquid helium (red) and remaining liquid helium bath after cooling (blue) as functions of temperature. The inset shows the region around the lambda point.

There are two situations that drive the requirement of minimum pumping speed necessary for operation of a liquid helium cooled cryostat at temperatures below 4.2 K. One is the process of cooling to a given temperature in a specified time frame and the other is maintaining the cooled bath at that given temperature for a specified heat load.

Table B.1 below shows the calculations of the cool down of liquid helium from its boiling temperature at atmospheric temperature (4.2 K) to lower temperatures for a 1 liter bath[2]. Values for the specific heat and vapor pressure[3] are taken from the tables on page 119 of The Physicist's Desk Reference (1989), by Russell J. Donnelly. The latent heat values are from Table 4.1 of

[2] Note that the specific heat of liquid helium at 4.2 K is typically much higher than other materials at this temperature, and thus the only significant source of heat capacity at cryogenic temperatures is the helium bath itself.

[3] These values differ slightly from the more recent values as listed in the International Temperature Scale of 1990 (ITS-90).

Helium-3 and Helium-4 (1969), by William E. Keller. As the pressure is reduced, energy is removed from the bath by the conversion of helium from liquid to gas, which is then pumped away. Each row of the table is for a reduction of the temperature by ΔT. The column entitled ΔVol lists the amount in liters of liquid evaporated to accomplish that temperature change, and the second column after that lists that amount in moles, after conversion by the molar volume (V_m). The final column lists the volume of gas pumped away at room temperature at the vapor pressure corresponding to the bath temperature, and is calculated using the ideal gas law:

$V = 1000*nRT/P$,

where n is the number of moles, R is the gas constant (8.314 J K^{-1} mol^{-1}), and the pressure is first converted to Pascals. The factor of 1000 converts the result to liters.

For temperatures down to 2.2 K from 4.2 K, the calculations were performed step-wise from numbers in the table. From 2.2 K to 2.1 K, i.e., through the lambda point, the calculations were integrated assuming the functional form of the lambda point as presented by Simanta & Jain (2006). The form they use is $C_s = -A*\ln(1-T/T_\lambda)+B$, where A and B are constants determined from fitting experimental data and T_λ is the temperature of the lambda point. Although this form is divergent at the lambda point, experiments have shown that gravitationally induced pressure gradients limit the specific heat to a value of about 86 J/mol/K (Lipa et al. 2003). The definite integral of this function is $A(T_\lambda-T)(\ln(1-T/T_\lambda)-1)+BT$, and the table entries for the temperature steps between 2.2 and 2.1768 and between 2.1768 and 2.1 were computed following this integral.

The table shows that to reach 2.2 K from 4.2 K requires pumping of about 850 liters of gas per liter of liquid helium in the bath and a consumption of about 24% of the bath volume. To then get over the lambda point to 2.1 K, a mere 100 mK reduction, requires an additional 560 liters of gas. Though the specific heat drops quickly on the low temperature side of the lambda point, so does the vapor pressure and thus to cool further requires even increasingly larger volumes of gas to be pumped out. As an example, FIFI-LS has a 3.12 liter bath that is pumped. To reach 1.6 K, requires about 12000 liters of gas to be pumped. If this is to be accomplished in less than two hours, a minimum pumping speed of about 2.25 liters/sec is required. About a third of the original liquid bath volume is consumed in this process.

Temp (K)	ΔT (K)	C_s (J/mol/K)	ΔE (J/mol)	L (J/mol)	ΔE/L	Bath Vol (L)	ΔVol (L)	V_m (L/mol)	mol	Vapor pressure (torr)	Vol at 297K (L)
4.2	0.2	17.323		82.34		1.0	0	0.032	0	749	
4.0	0.2	15.991	3.331	86.56	0.039	0.961	0.039	0.031	1.25	616	33.9
3.8	0.2	14.385	3.038	89.53	0.035	0.927	0.033	0.030	1.08	500	35.7
3.6	0.2	13.048	2.743	91.64	0.030	0.899	0.028	0.030	0.93	400	38.4
3.4	0.2	11.859	2.491	92.99	0.027	0.875	0.024	0.029	0.82	315	42.6
3.2	0.2	10.807	2.267	93.75	0.024	0.854	0.021	0.029	0.73	242	48.8
3.0	0.2	9.951	2.076	93.91	0.022	0.835	0.019	0.028	0.66	182	57.8
2.8	0.2	9.358	1.931	93.58	0.021	0.818	0.017	0.028	0.61	133	71.8
2.6	0.2	9.088	1.844	92.80	0.020	0.802	0.016	0.028	0.58	93.7	94.9
2.4	0.2	9.530	1.862	91.73	0.020	0.785	0.016	0.028	0.59	63.3	138
2.2	0.20	16.166	2.570	90.75	0.028	0.763	0.022	0.027	0.81	40.5	288
2.1768	0.02	86	0.50	90.75	0.006	0.759	0.004	0.027	0.16	38.6	75
2.1	0.08	29.54	3.01	93.13	0.033	0.734	0.025	0.027	0.92	31.4	486
2.0	0.1	21.10	2.53	93.13	0.027	0.714	0.020	0.027	0.73	23.5	488
1.8	0.2	11.93	3.30	92.72	0.036	0.689	0.025	0.028	0.92	12.3	943
1.6	0.2	6.48	1.84	90.74	0.020	0.675	0.014	0.028	0.50	5.69	1023
1.4	0.2	3.12	0.96	87.76	0.011	0.668	0.007	0.027	0.26	2.16	1248

Once the target temperature is reach, the required pumping speed to maintain that temperature is dependent on the heat leak into the bath. In the case of infrared instrumentation, the heat leak is primarily due to the operation of the detectors if the cryogen bath is well isolated thermally from the environment. For a given heat load (h) that needs dissipating, liquid helium needs to be evaporated at a rate of dn/dt (mol sec^{-1}) of approximately

$$dn/dt = h/L(T),$$

where h is in Watts (J sec^{-1}) and the latent heat L is in J mol^{-1}. The latent heat of liquid helium at temperatures below the lambda point is a weak function of temperature, with values between 80 and 93 J mol^{-1}. If the vacuum pump is at room temperature (297 K), then the volume pumping speed can be determined from the time derivative of the ideal gas law:

$$dV/dt = nRT/P = hRT/LP$$

Where P is the vapor pressure of liquid helium at temperature T. For example, to achieve a fixed temperature of 1.8 K at a vapor pressure of 12.47 Torr (1662 Pascals), with a heat load of 300 mW, we get

$dV/dt = 0.300\ J\ sec^{-1} * 8.314\ J\ K^{-1}\ mol^{-1} *297\ K / (92.72\ J\ mol^{-1} * 1662\ J\ m^{-3})$

$dV/dt = 4.9\ L\ sec^{-1}$

This is a quickly changing function of temperature. At 1.6 K, which has a vapor pressure of 5.69 Torr, $dV/dt = 10.7\ L\ sec^{-1}$.